Numerical Study of Improving Aerodynamic Performance of Low Solidity LPT Cascade through Increasing Trailing Edge Thickness

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This paper presents a new idea to reduce the solidity of low-pressure turbine (LPT) blade cascades, while remain the structural integrity of LPT blade. Aerodynamic performance of a low solidity LPT cascade was improved by increasing blade trailing edge thickness (TET). The solidity of the LPT cascade blade can be reduced by about 12.5% through increasing the TET of the blade without a significant drop in energy efficiency. For the low solidity LPT cascade, increasing the TET can decrease energy loss by 23.30% and increase the flow turning angle by 1.86% for Reynolds number (Re) of 25,000 and freestream turbulence intensities (FSTI) of 2.35%. The flow control mechanism governing behavior around the trailing edge of an LPT cascade is also presented. The results show that appropriate TET is important for the optimal design of high-lift load LPT blade cascades.

Keywords: Aircraft engine, low pressure turbine, trailing edge thickness, profile loss, flow control

Introduction

Optimization of turbomachinery design requires minimizing manufacturing and operating costs, while maintaining high system efficiency. In low pressure turbines (LPTs), this can be achieved by reducing the number of blades per row, however the reduction in blade number results in an increased load acting on each blade [1]. High-performance LPTs typically operate at low Reynolds numbers and often suffer from flow separation on the suction sides, decreasing efficiency and reducing performance of the blade [2]. One way to improve the aerodynamic performance of LPTs is to control the flow separation [3,4].

Various flow control devices have been used in LPTs to control flow separation. Passive devices, such as those used by Lake et al. [5] and Rouser et al. [6] include dimples, grooves, and trips on the suction surface to control flow separation. In another study, Van Treuren et al. [7] used vortex generators to control flow separation, while Murawski and Vafai [8] considered changing the axial chord of the blade. Finally, Byerley et al. [9] considered Gurney flaps to control boundary layer separation. Active devices have also been developed to control flow separation. Huang et al. [10] utilized single plasma actuators placed at different chord locations to control boundary layer separation, while Liu et al. [11], Bons et al. [12-14] and Bernardini et al. [15] considered Vortex Generator Jets (VGJs).

The primary LPT blade profile loss is due to flow separation, however, the wake loss is also important. Wake loss can be reduced by changing the trailing edge thickness or by altering the shape of the trailing edge [16,17]. Zhou et al. [18] improved aerodynamic performance of LPT blades by increasing the trailing edge thickness (TET) of the blade. For a higher lift cascade, increasing TET can increase trailing edge static pressure and reduce the wake loss.

Recently, there has been a focus on developing low solidity and highly-loaded low solidity LPT cascade blades. Sondergaard et al. [19] used the VGJs to decrease the solidity of the LPT cascade Pack B, while Qiao et al. [4,20] used the jet-flap and Gurney-flap to decrease energy loss, which induced a reduction in the solidity of the LPT cascade Pack B while maintained high efficiency. In these studies, active devices (VGJs and jet flap) and passive devices (Gurney-flap) were applied to the blade to control the flow separation in low solidity LPT cascades, which increases the manufacturing cost and damages the structural integrity of the blade.

Inspired by improving aerodynamic performance of LPT blades by increasing the TET of the blade, we have

an idea that the solidity may be reduced by only increasing the TET of blade, with thought toward reducing the blade count and maintaining the structural integrity of the blade. To authors' knowledge, we are the first to study the feasibility of reducing the solidity of LPT blade cascades by increasing the TET of LPT blades. We present flow control effects resulting from increasing TET of LPT blades.

Computation model and method

Geometric Model

Figure 1 gives geometry of the P&W Pack B. The chord length of the Pack B blade is C=17.78 cm. The pitch length is s=14.12 cm and the axial chord length is C_x=15.95 cm. The inlet flow angle (β1) and the designed exit flow angle (β2) for the blade are 35° and -60° respectively. The solidity τ (defined as C/s) of the cascade is 1.25, which is the optimum cascade solidity for conventional design.

Increasing the TET was accomplished by only changing the profile of the blade on the pressure side at about 95% chord of the airfoil, as shown in Figure 2. The TET h is shown in Figure 2. The standard TET of Pack B is h/s = 1.7%.

Computation Mesh and Computation Methods

For numerical simulations, a multi-block structured grid was used. The blade was surrounded by an O-grid, with the first layer near the wall prescribed at 0.015 mm and a grid expansion ratio of 1.12. The y+ of the blades was less than 0.5. Figure 3 shows the computational grids for simulations.

Two-dimensional RANS equations were solved to describe flow around the LPT blade profile. Flow separation and transition was solved using the Langtry-Menter transition model [21,22].

The inlet total pressure, flow angle, eddy viscosity coefficient, and total temperature were specified at the inlet boundary. The outlet boundary specified static pressure. A periodic condition was used to only simulate one blade.

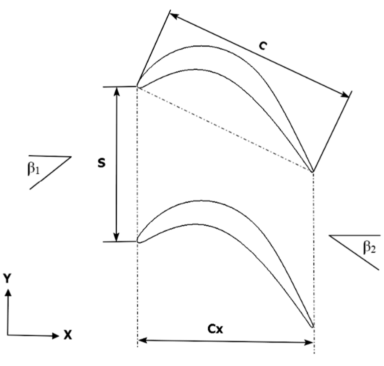


Fig. 1 Geometry of the LPT cascade

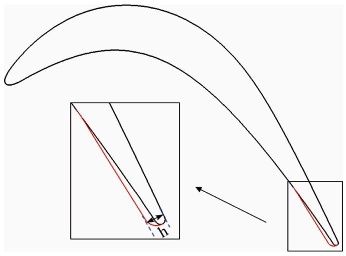


Fig. 2 Increasing the thickness of Pack B trailing edge

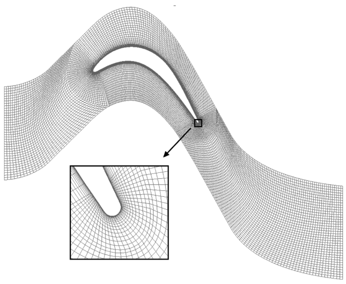


Fig. 3 Computational grids

Validation of the numerical method

To verify the numerical methods, the computational data were compared with experimental data [5,6,10].

The wall pressure coefficient C_p is defined as:

$$C_p = \frac{P_s - P_{inlet}}{0.5\rho U_{inlet}^2} \tag{1}$$

Where ρ is the inlet air density, U_{inlet} is the inlet velocity, P_s *is* the static pressure on the blade surface, and P_{inlet} is inlet static pressure.

The energy loss coefficient γ based on the inlet velocity U_{inlet} is defined as:

$$\gamma = \frac{P_{inlet}^* - P_{outlet}^*}{0.5\rho U_{inlet}^2} \tag{2}$$

Where P_{inlet}^* is inlet stagnation pressure and P_{outlet}^* is outlet stagnation pressure.

The energy loss coefficient ω based on the outlet velocity U_{outlet} is defined as:

$$\omega = \frac{P_{inlet}^* - P_{outlet}^*}{0.5\rho U_{outlet}^2} \tag{3}$$

Where U_{outlet} is the outlet velocity.

In Figure 4, the computed pressure coefficient distributions are shown along with experimental data. The computed C_p distributions on the blade show good agreement with experimental data. These results show that computational methods have the ability to predict flow separation and transition. At a given FSTI, decreasing the Re moves the location of separation upstream and

the location of reattachment downstream. For a given Reynolds number, increasing the FSTI moved the location of separation downstream and the location of reattachment upstream.

A comparison of computed energy loss coefficients with experimental results is shown in Figure 5. Computed data display good agreement with experimental

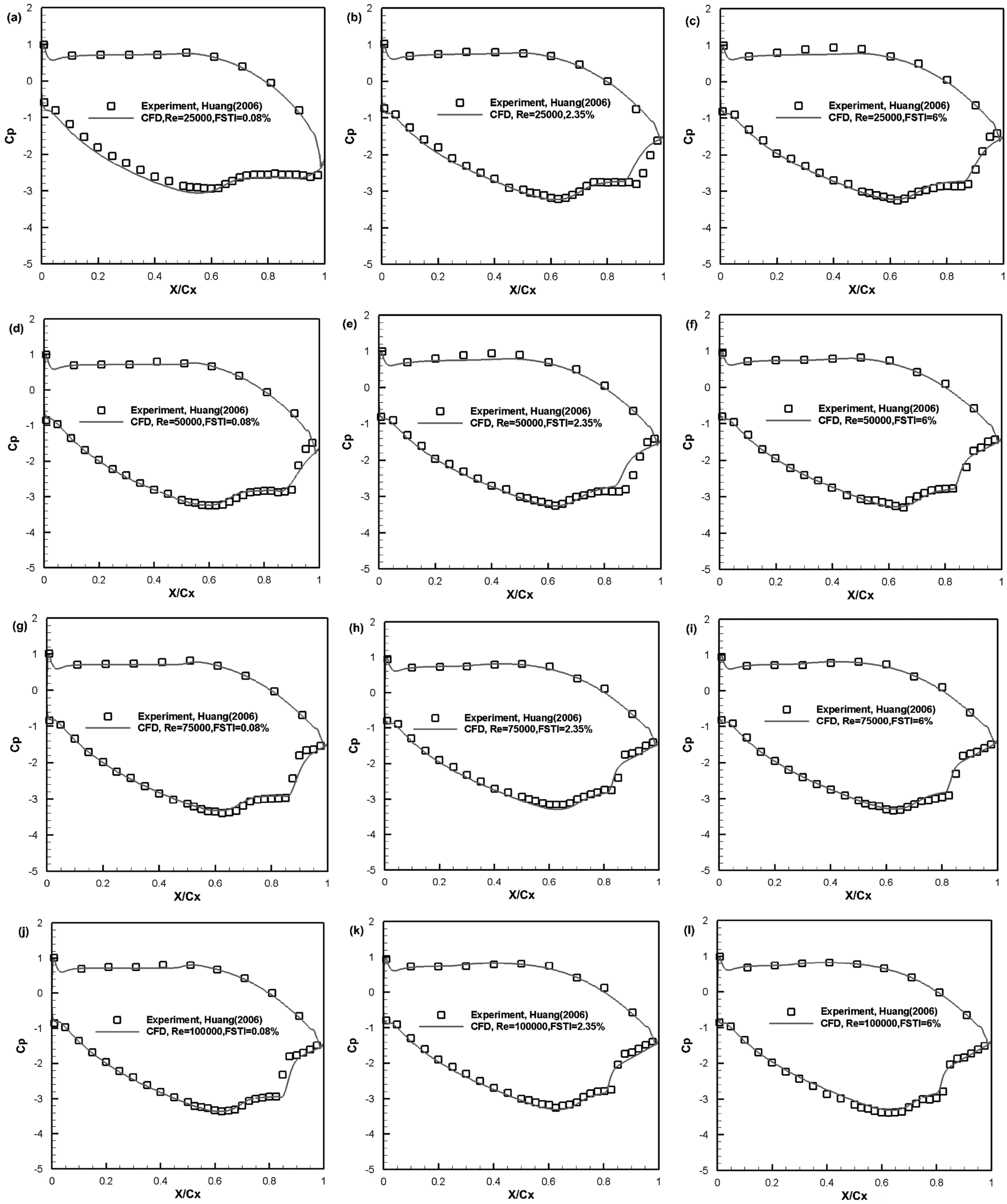


Fig. 4 Blade pressure coefficient distributions

data for Re = 86,000 and Re = 172,000, as shown in Figure 5(a), however the computed values overestimate experimental data for Re = 25,000 and Re = 50,000. As shown in Figure 5(b), for Re = 25,000, the computed values were in good agreement with experimental values for FSTI = 1%, but computed values were slightly lower than experimental data for FSTI = 4%. At Re = 45,000, the computed data and the experimental data exhibited large differences when FSTI = 1%, which may be caused by flow instability; however the computed data and the

experimental data showed good agreement when FSTI = 4%. At Re = 100,000 the computed loss coefficient matched experimental values for both FSTI = 1% and FSTI = 4%. Based on fit to experimental data, the computation method used in this work is able to describe flow separation and transition in the turbine cascade.

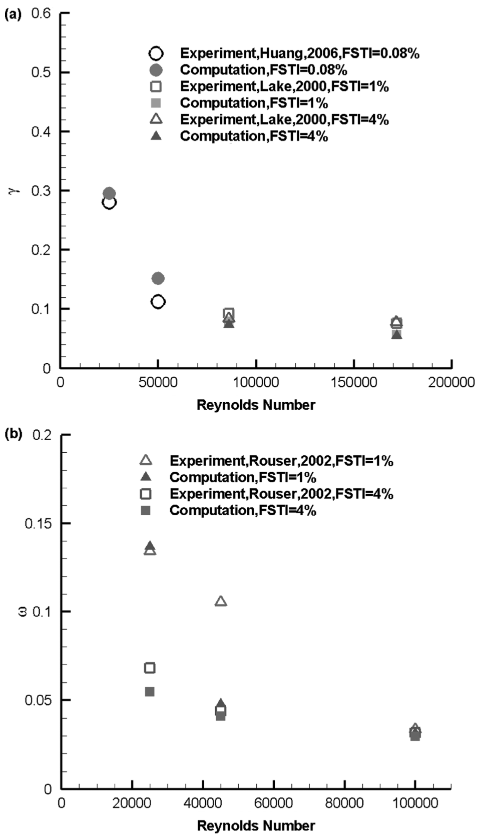


Fig. 5 Comparison of computed energy loss coefficients with experimental results

Effect of TET on the low solidity LPT cascades

To decrease the blade count, the solidity of the LPT cascades reduced by 12.5% and 25%, which were respectively referred as Pack LB1 and Pack LB2. The solidity of the LPT cascades was changed by only increasing the pitch of the cascade with the other airfoil parameters unchanged.

To improve aerodynamic performance of the low solidity LPT, the TET of the blade increases. Table 1 shows the changes in TET.

Figure 6 shows the effect of TET on the energy loss coefficient in the two low solidity cascades. As shown, for Pack LB1, the energy loss coefficient first decreases and then increases at Re = 25,000, FSTI = 2.35% as the TET increases; The energy loss coefficient of Pack LB1 blades with TET of 4%s decreases by 23.30% compared to the coefficient for a standard trailing edge at Re = 25,000, FSTI = 2.35%; The energy loss coefficient increases at higher Reynolds number and higher FSTI. However, increasing TET cannot reduce the energy loss coefficient in the lower solidity cascade Pack LB2.

Figure 7 shows the effect of TET on the turning angle in the two low solidity cascades. As shown in Figure 7, the turning angle of the two low solidity cascades increase as TET increases. The turning angle increases by 1.86% at Re=25,000, FSTI=2.35% with a TET of 4.0%s

Table 1 Changes in trailing edge thickness

h (mm)	2.4	4.5	5.6	6.5	10.6
h/s	1.7%	3.2%	4.0%	4.6%	7.5%

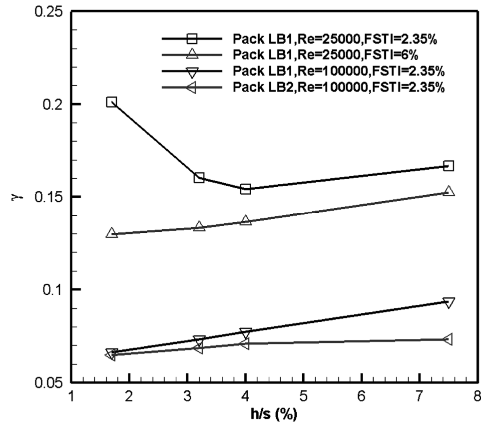


Fig. 6 Effect of TET on the energy loss coefficient in the two low solidity cascades

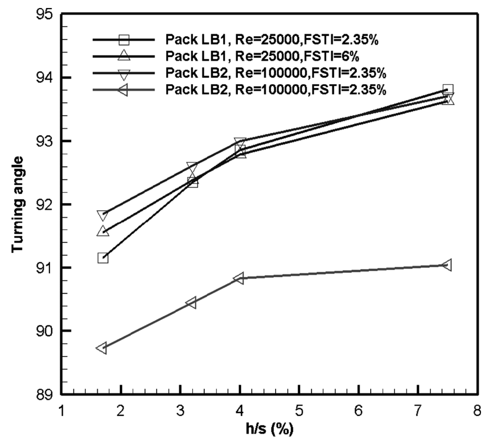
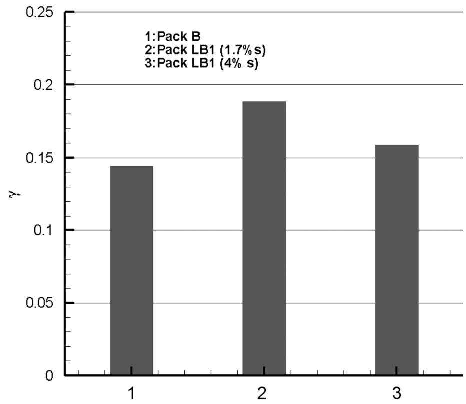


Fig. 7 Effect of TET on turning angle in a low solidity cascade

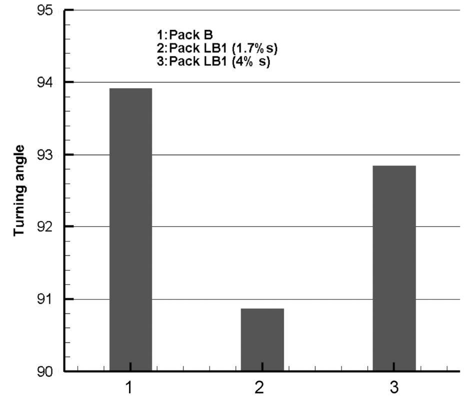
in the Pack LB1. Figure 6 and Figure 7 together show an interesting result that increased TET enhanced aerodynamic performance of low solidity LPT cascade; however increasing TET couldn't suppress flow separation when the solidity is too low.

Figures 8 shows aerodynamic performance of a blade cascade with trailing edge thickness 4.0%s at Re = 25,000, FSTI = 2.35%. As shown in Figure 8(a), the energy loss coefficient of a low solidity Pack LB1 with a TET of 4.0%s can be manipulated to be equivalent to that of a

Pack B cascade. As shown in Figure 8(b), the turning angle of a low solidity Pack LB1 cascade with a TET of 4.0%s is about 1° lower than that of a Pack B cascade, which is about 2° higher than that of Pack LB1 cascade with standard TET. These results show that aerodynamic performance of a low solidity Pack LB1 cascade can nearly match that of a Pack B cascade by increasing the TET.



(a) Energy loss coefficient



(b) Turning angle

Fig. 8 Aerodynamic performance of a blade cascade with trailing edge thickness 4.0%s at Re = 25,000, FSTI = 2.35%

The static pressure coefficient C_{pb} is defined as:

$$C_{pb} = \frac{P_p - P_{outlet}}{0.5\rho U_{inlet}^2} \tag{4}$$

where P_{outlet} is outlet static pressure, P_p is the blade trailing edge plane static pressure.

Figure 9 shows the static pressure coefficient C_{pb} at Re = 25,000, FSTI = 2.35%. As shown in Figure 9, the positive static pressure coefficient area of a low solidity cascade with increased TET differs from the coefficient of a Pack B cascade, which is larger than the coefficient for a Pack LB1 cascade with standard TET. Increasing the positive static pressure coefficient C_{pb} area accelerates the trailing edge flow and reduces wake loss. However, increasing TET enhances the trailing edge flow mixture, which increases the wake loss. The total wake loss results from the combination of these two effects.

Compared with the technologies in references [19-21], increasing TET doesn't need add other devices in the blade, which decreases the manufacturing cost and remains the structural integrity of the LPT blade.

Figure 10 shows the pitch-wise energy loss coefficient distribution on a plane near the trailing edge at Re = 25,000, FSTI = 2.35%. The pitch-wise energy loss coefficient of the low solidity cascade with a TET of 4%s is slightly larger than that of a Pack B cascade, which is smaller than that of a Pack LB1 cascade with standard trailing edge. Increasing TET decreases the width and intensity of the wake. The center of the Pack LB1 cascade wake moves towards the pressure side as the TET increases.

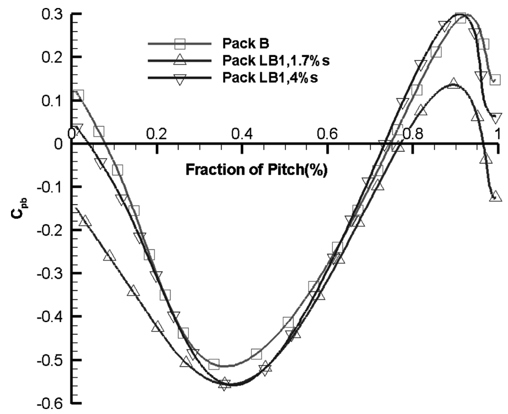


Fig. 9 The static pressure coefficient C_{pb} at Re = 25,000, FSTI = 2.35%

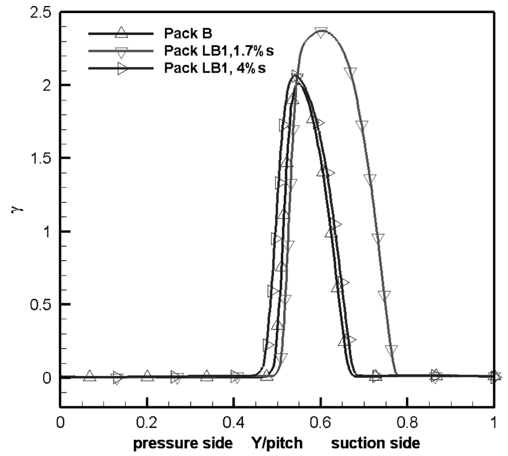


Fig. 10 The pitch-wise energy loss coefficient distribution on a plane near the trailing edge at Re = 25,000, FSTI = 2.35%

Figures 11 and 12 respectively show streamline and velocity contours and turbulence kinetic energy contours in the low solidity LPT cascades at Re = 25,000, FSTI = 2.35%. For a low solidity cascade blade with standard TET, there is severe flow separation on the suction sur-

face, as shown in Figure 11(a). With TET of 4.0%s, the flow separation is significantly reduced, as shown in Figure 11(b). As TET increases from 4.0%s to 7.5%s, the size of the separation bubble decreases slightly, as shown in Figure 11(c). As shown in Figure 12, increasing TET decreases the turbulence kinetic energy on the suction surface. However, the turbulence kinetic energy near the trailing edge increases when TET is very large.

The increase in trailing edge thickness deflects the main stream, which results in accelerating flow on the adjacent airfoil suction surface. This can increase energy in the boundary layer on the suction surface, which increases resistance to flow separation. As a result, the location of separation moves downstream and the boundary-layer separation zone becomes smaller.

Conclusions

This work presents a new idea to decrease the solidity of LPT blade cascades by increasing the TET. In the low solidity LPT cascades, aerodynamic performance can be improved by increasing the thickness of the trailing edge. With an increased TET, the solidity of the LPT cascade can be reduced by 12.5% without the significant loss. When the solidity of LPT cascade is reduced by about 12.5%, increasing the thickness of trailing edge can decrease energy loss by 23.30% and increase turning angle by 1.86% at Re=25,000 and FSTI=2.35%.

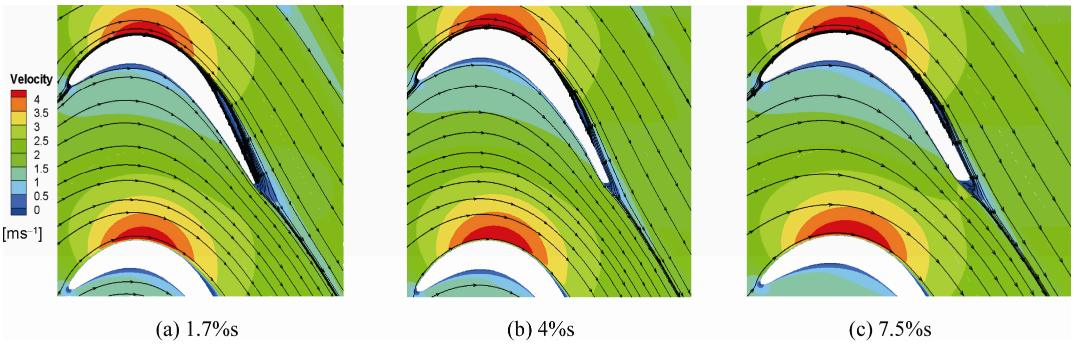


Fig. 11 Streamline and velocity contours in the low solidity LPT cascade Pack LB1 at Re=25,000, FSTI=2.35%

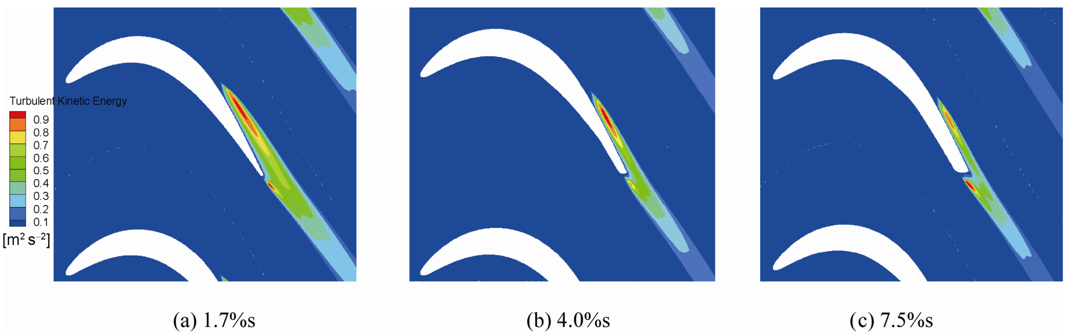


Fig. 12 Turbulence kinetic energy contours in the low solidity LPT cascade Pack LB1 at Re=25,000, FSTI=2.35%

There are three main effects of increasing the thickness of trailing edge. (1) The main stream deflected, which results in accelerating flow on the adjacent airfoil suction surface. This can increase energy in the boundary layer, which increases resistance to flow separation and decreases the boundary-layer loss. (2) The trailing edge plane static pressure increases, which reduces the wake loss. (3) The trailing edge flow mixture is enhanced, which increases the wake loss. The profile loss results from the combination of these three effects.

It is generally thought that increasing the airfoil lift and controlling the flow separation need to add active or positive devices, while our work shows that the solidity of the LPT cascade can be reduced by only increasing the TET. Compared with the previous technologies, the new idea presented in this work decreases the manufacturing cost and remains the structural integrity of the LPT blade. This work provides some new guidelines for the design of high-lift load LPT blade cascades.

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